Final Report for Period: 08/2010 - 08/2010 **Submitted on:** 06/04/2011
Principal Investigator: Citrin, David S. **Award ID:** 0523923
Organization: Georgia Tech Research Corp

Submitted By:
Citrin, David - Principal Investigator

Title:
Enabling Foundations of Nanoplasmonics

Project Participants

Senior Personnel

Name: Citrin, David
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Xia, Zhixuan
Worked for more than 160 Hours: Yes
Contribution to Project:
Developed code and carried out electromagnetic simulations.

Name: Rontani, Damien
Worked for more than 160 Hours: Yes
Contribution to Project:
Worked on nonlinear dynamics in lasers.

Name: Backes, Thomas
Worked for more than 160 Hours: Yes
Contribution to Project:
Worked on surface-polariton dispersion in two-dimensional nanoparticle arrays.

Name: Kim, Dong Kwon
Worked for more than 160 Hours: Yes
Contribution to Project:
Worked on electro-optic effect in quantum wells.

Name: Bai, Jing
Worked for more than 160 Hours: Yes
Contribution to Project:
Worked on intracavity nonlinearities in quantum-cascade lasers.

Name: Kim, Dae Sin
Worked for more than 160 Hours: Yes
Contribution to Project:
Worked on THz dynamics.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Huazhong University of Sci and Technol

HUST grad student Junbo Feng spent eight months of the review period in my group at Georgia Tech carrying out structure fabrication. Costs were born by HUST. In addition, the PI spent one month at the expense of HUST at HUST. Prof. Zhiping Zhou's group of HUST has also been providing theoretical support and optical characterization.

Technical University of Troyes, France

University of Minnesota-Twin Cities

Prof. Ruden and I coadvised PhD student Chi-Ti Hsieh who worked on the theory of light emission from carbon nanotube field effect transistors.

Federal University of Campina Grande

Prof. Adriano Batista and I worked on THz npnlinear dynamics in quantum wells.

Other Collaborators or Contacts

Prof. Chris Summers, School of Materials Science and Engineering, Georgia Institute of Technology

Prof. Zhiping Zhou, Huazhong University of Science and Technology, Wuhan, PR China

Prof. Hamza Kurt, TOBB University of Economics and Technology, Ankara, Turkey

Prof. Abdallah Ougazzaden, School of Electrical and Computer Engineering, Georgia Institute of Technology

Prof. Diddier Lippens, IEMN, Lille, France

Prof. Andrei Fedorov, School of Mechanical Engineering, Geogia Institute of Technology

Prof. Pascal Royer and Dr. Detrio Mascias, Technical University of Troyes, France

Activities and Findings

Research and Education Activities:

We have conducted simulations of the optical properties of periodic arrays of metal nanoparticles in conjunction with other optical media, such as an optical gain medium. We have focused on two-dimensional nanoparticle arrays and continued work on quantum-cascade lasers to explore integration of nanoparticle structures with these devices. In addition, we have been exploring photothermal effects for nanoscale heating in collaboration with Prof. Andrei Federov of the School of Mechanical Engineering at Georgia Tech.

Findings:

Please see attached file.

Training and Development:

The six graduate students funded under this program have carried out a range of simulations of various physical properties of nanoparticle arrays and related phenomena that are being used in conjunction with the arrays. These include the optical and thermal properties of metal nanoparticle arrays and the laser characteristics of quantum-cascade lasers. In all case, the students have had to master the theory as well as write their own code to solve the problems.

Outreach Activities:

The PI has given a number of seminars and colloquia--primarily in Europe but also in Brazil--in a general science or engineering context to broaden awareness of nanoplasmonics. He has also hosted a graduate student from Huazhong University of Science and Technology (HUST), PR Wuhan, China.

Journal Publications

Chen, Y; Feng, JB; Zhou, ZP; Yu, J; Summers, CJ; Citrin, DS, "Fabrication of silicon microring resonator with smooth sidewalls", JOURNAL OF MICRO-NANOLITHOGRAPHY MEMS AND MOEMS, p. , vol. 8, (2009). Published, 10.1117/1.325848

Lerche, I; Tautz, RC; Citrin, DS, "Terahertz-sideband spectra involving Kapteyn series", JOURNAL OF PHYSICS A-MATHEMATICAL AND THEORETICAL, p. , vol. 42, (2009). Published, 10.1088/1751-8113/42/36/36520

Yi, HX; Citrin, DS; Zhou, ZP, "Highly sensitive silicon microring sensor with sharp asymmetrical resonance", OPTICS EXPRESS, p. 2967, vol. 18, (2010). Published,

Yi, HX; Citrin, DS; Chen, Y; Zhou, ZP, "Dual-microring-resonator interference sensor", APPLIED PHYSICS LETTERS, p. , vol. 95, (2009). Published, 10.1063/1.326372

Kim, DK; Citrin, DS, "Electrooptic properties of InGaAsP asymmetric double quantum wells: Enhanced slope efficiency in waveguide electroabsorption modulators", IEEE JOURNAL OF QUANTUM ELECTRONICS, p. 765, vol. 43, (2007). Published, 10.1109/JQE.2007.90278

Kim, DK; Citrin, DS, "Electric-field-induced strong mixing between e1-hh1 and e1-hh2 excitons in asymmetric double quantum wells", PHYSICAL REVIEW B, p. , vol. 76, (2007). Published, 10.1103/PhysRevB.76.12530

Kim, DK; Citrin, DS, "1 THz modulation in InGaAsP multiple quantum wells for 40 Gb/s applications", IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, p. 416, vol. 14, (2008). Published, 10.1109/JSTQE.2007.91175

D. K. Kim and D. S. Citrin, "Strong excitonic mixing effect in asymmetric double quantum wells: On the performance of electroabsorption modulators", Phys. Stat. Sol. (c), p. 2400, vol. 5, (2008). Published,

Kurt, H; Hao, R; Chen, Y; Feng, J; Blair, J; Gaillot, DP; Summers, C; Citrin, DS; Zhou, Z, "Design of annular photonic crystal slabs", OPTICS LETTERS, p. 1614, vol. 33, (2008). Published,

Kurt, H; Citrin, DS, "Reconfigurable multimode photonic-crystal waveguides", OPTICS EXPRESS, p. 11995, vol. 16, (2008). Published,

Kurt, H; Citrin, DS, "A novel optical coupler design with graded-index photonic crystals", IEEE PHOTONICS TECHNOLOGY LETTERS, p. 1532, vol. 19, (2007). Published, 10.1109/LPT.2007.90385

Hou, J; Wu, HM; Citrin, DS; Mo, WQ; Gao, DS; Zhou, ZP, "Wideband slow light in chirped slot photonic-crystal coupled waveguides", OPTICS EXPRESS, p. 10567, vol. 18, (2010). Published,

Gao, DS; Zhou, ZP; Citrin, DS, "Self-collimated waveguide bends and partial bandgap reflection of photonic crystals with parallelogram lattice", JOURNAL OF THE OPTICAL SOCIETY OF AMERICA A-OPTICS IMAGE SCIENCE AND VISION, p. 791, vol. 25, (2008). Published,

Citrin, DS, "Laser physics - A phase it's going through", NATURE, p. 669, vol. 449, (2007). Published, 10.1038/449669

J. Bai and D. S. Citrin, "Design of nonlinearity-enhanced quantum-cascade lasers", Optics and Quantum Electronics, p. 191, vol. 40, (2008). Published, Citrin, DS; Wang, Y; Zhou, ZP, "Far-field optical coupling to semi-infinite metal-nanoparticle chains", JOURNAL OF THE OPTICAL SOCIETY OF AMERICA B-OPTICAL PHYSICS, p. 937, vol. 25, (2008). Published,

Hsieh, CT; Citrin, DS; Ruden, PP, "Recombination-mechanism dependence of transport and light emission of ambipolar long-channel carbon-nanotube field-effect transistors", APPLIED PHYSICS LETTERS, p. , vol. 90, (2007). Published, 10.1063/1.242902

Backes, TD; Citrin, DS, "Plasmon Polaritons in 2-D Nanoparticle Arrays", IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, p. 1530, vol. 14, (2008). Published, 10.1109/JSTQE.2008.200791

Backes, TD; Citrin, DS, "Excitation of nonradiative surface-plasmon-polariton beams in nanoparticle arrays", PHYSICAL REVIEW B, p. , vol. 78, (2008). Published, 10.1103/PhysRevB.78.15340

Yi, HX; Citrin, DS; Zhou, ZP, "Highly Sensitive Athermal Optical Microring Sensor Based on Intensity Detection", IEEE JOURNAL OF QUANTUM ELECTRONICS, p. 354, vol. 47, (2011). Published, 10.1109/JQE.2010.209003

Books or Other One-time Publications

Benjamin Zaks, Dominik Stehr, Stephen Hughes, Alex Maslov, David Citrin, Mark Sherwin, "Asymmetric Autler-Townes Effect in THz-Driven Quantum Wells: Beyond the Three State and Rotating Wave Approximations", (2010). Conference Proceedings, Accepted
Collection: Proceedings of the Conference on Lasers and Electro-Optics (CLEO) 2010
Bibliography: Published online at www.osa.org

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

We have continued to supply to the community a set of analytic techniques that enable closed-form solution to various problems--in particular those involving gain media. This is enabling progress in an area where central problems might otherwise be intractible.

In addition, we have introduced the idea of vector optical filters based on noble-metal nanoparticle arrays and dielectric interfaces. This is fundamentally different from using various spatially varying gratings or diffractive elements, in that the nanoparticle array functions as a spatially uniform metamaterial.

Contributions to Other Disciplines:

Under this program, we have been exploring the use of nanoplasmonic structures to control photothermal effects in media incorporating metal nanoparticles. Namely, we are working on the use of nanoparticle clusters, chains, and arrays to attain nanoscale control of heat delivery into the embedding medium.

The paper Lerche, I; Tautz, RC; Citrin, DS, 'Terahertz-sideband spectra involving Kapteyn series,' J. PHYS. A, 2009 carries out a closed form summation of a series of Bessel functions that has hitherto not been performed.

In studying the nonlinear dynamics of lasers in preparation to coupling them to nanoparticle systems, we have identified novel ways to multiplex chaotically encrypted signals.

Contributions to Human Resource Development:

Six graduate students were partially supported by this project. These students obtained advanced training in the science and engineering of metal nanoparticles and other optical media to be used in conjunction with the nanoparticles. A visiting graduate Jin Hou student from

Huazhong University of Science and Technology (who did not receive financial support from the program) worked in my group from October 2009 to present on photonic crystals, including in some cases metallic structures.

Contributions to Resources for Research and Education:

Work under this program has helped to cement a cooperation with students and researchers at HUST, Wuhan, China. We have also begun to explore a cooperation with Prof. Pascal Royer of the Technical University of Troyes, France. His group works in part on photothermal effects of nanoparticles in conjunction with other media.

Contributions Beyond Science and Engineering:

Conference Proceedings

Bai, J;Citrin, DS, Harmonic-resonance enhanced third-harmonic generation and Kerr-effect in mid-infrared quantum-cascade lasers - art. no. 699707, "APR 07-09, 2008", SEMICONDUCTOR LASERS AND LASER DYNAMICS III, 6997: 99707-99707 2008

Bai, J;Citrin, DS, Design of nonlinearity-enhanced quantum-cascade lasers, "MAR 28-30, 2007", OPTICAL AND QUANTUM ELECTRONICS, 40 (2-4): 191-195 MAR 2008

Hao, R;Kurt, H;Citrin, DS;Zhou, ZP, The complete bandgap in ring-shaped photonic crystal SOI slab, "SEP 17-19, 2008", 2008 5TH IEEE INTERNATIONAL CONFERENCE ON GROUP IV PHOTONICS, : 291-293 2008

Hao, R;Mao, A;Feng, J;Gao, D;Zhou, Z;Citrin, DS, Silicon based ultra-compact modulator with photonic crystal - art. no. 67820Z, "NOV 02-05, 2007", OPTOELECTRONIC MATERIALS AND DEVICES II, 6782: Z7820-Z7820 Part 1-2 2007

Hsieh, CT;Citirin, DS;Ruden, PP, Photoconductivity of Ambipolar Long-Channel Carbon-Nanotube Field-Effect Transistors, "MAY 04-09, 2008", 2008 CONFERENCE ON LASERS AND ELECTRO-OPTICS & QUANTUM ELECTRONICS AND LASER SCIENCE CONFERENCE, VOLS 1-9, : 2461-2462 2008

Rontani, D;Locquet, A;Sciamanna, M;Citrin, DS, Masking the time-delay of the chaotic output of an external-cavity laser - art. no. 69970D, "APR 07-09, 2008", SEMICONDUCTOR LASERS AND LASER DYNAMICS III, 6997: D9970-D9970 2008

Categories for which nothing is reported:

Any Web/Internet Site

Any Product

Contributions: To Any Beyond Science and Engineering

0523923 Enabling Foundations of Nanoplasmonics
Findings for Period 08/01/2006-07/31/2010

PI: David S. Citrin

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Georgia Institute of Technology
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The following is a final report of the main findings for program 0523923 *Enabling Foundations of Nanoplasmonics* during the period 08/01/2006-07/31/2010.

The work carried out leveraged off our results from the prior year under this program, in particular calculations of surface-plasmon-polariton (SPP) dispersion and radiative loss in planar periodic arrays of nanoparticles, as reported previously. This work had focused on SPP modes guided in effect by a layer of noncontacting noble-metal nanoparticles (NP) on a dielectric substrate. This work used semianalytic techniques based on the coupled-dipole model to obtain the frequency of the modes and intrinsic diffractive losses as a function of excitation wavevector.

We have focused on the interaction of NP arrays (NPA) with optical fields incident from outside rather than guided modes. The aim is to understand if NPAs may provide functionality to serve as optical elements, such as lenses and filters. Below is a brief description of our results.

Background: Imaging with surface plasmon polaritons in metal nanoparticle arrays: The use of metals as an optical medium has been restricted due to optical losses from electron-electron scattering. In finite geometries, however, where part of the field exists outside the metal, such losses, though still severe, may not be severe enough to obviate optical applications. The electromagnetic modes in metal structures having a boundary with a dielectric are surface plasmons (SP). SPs in noble-metal (e.g., Au and Ag) NPs (and nanoshells and nanorods) are manifested as pronounced optical resonances. There is interest in structures composed of noncontacting metal NPs to exploit the electromagnetic coupling between between NPs. Early work sought to use the coupled modes involving 1D periodic NP chains (NPC) to act as waveguides, shown in Fig. 1 along with a 2D NPA. Such coupled modes are known as SPPs.[1] Because the transverse dimension of the chain is the NP size, perhaps ~10 nm, the NPC can act as a waveguide with geometric transverse dimension much less than $\lambda/2$, which is the limit for conventional dielectric waveguides. This in turn recommended SPPs in NPCs for nanoscale optical interconnects.

Unfortunately, the push toward such applications faltered. SPPs in NPCs are strongly attenuated—on the order of tens of NPs, the physical origin of which being resistive loss inherent to metals (nonradiative loss) and diffraction away from the NPC (radiative loss).

While these problems are formidable, there may be ways to solve them. Nanorods may suppress nonradiative losses. Citrin has also shown[2] that embedding the NPC in an optical gain medium can mitigate nonradiative losses. Insofar as the radiative losses are concerned, excitation of short wavelength SPPs whose excitation wavevector is too large to couple to far-field freespace propagating modes of the field will entirely suppress these losses. Clearly, there is work to be done to overcome these problems, though ways to solve these exist. We thus deem NPCs and NPAs worth pursuing even in view of the difficulties novel phenomena and applications based on the optical properties of NPCs and NPAs.

A key feature of SPPs in NPCs as well as in periodic 2D NPAs that make them of interest for imaging applications is the downward curvature with increasing excitation wavevector **k** in the structure of the dispersion curves for polarization perpendicular to the **k**. While Ruppin and Kempa[3] have pointed out this feature, there is no work to our knowledge verifying that such features are indeed useful. It is the rigorous exploration of this remarkable property and their use as nanoscale focusing optical elements that is the aim of the proposed project.

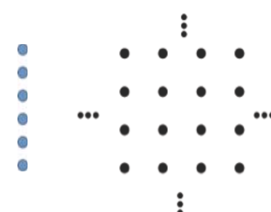

Fig. 1: Left: Nanoparticle chain; right, nanoparticle array.

We have and will continue study the electromagnetic properties of NPCs and NPAs in an imaging context. Specifically, we are exploring negative refraction (NR) in NPCs/NPAs based on a rigorous approach from vector Fourier optics. We aim to study the application of these structures for imaging with nanoscale optical elements and as filters to generate optical vector beams.

Basic Idea: SPs are localized electromagnetic modes at metal-dielectric interfaces. SP properties are different from either photons or electrons alone. While SPs suffer from high optical losses, noble-metal nanostructures in some cases allow for the control of new SP properties through the shape of the electromagnetic mode.

Moreover, as shown in Fig. 1, by allowing SPs on individual NPs to be coupled in 1D NPCs or 2D NPAs, delocalized excitations, known as SPP, in the composite structures are enabled. This opens the possibility of using NPCs and NPAs as building blocks for various applications in extreme subwavelength optics.

Pendry proposed[4] that a metal film can act as an imaging optical element, working like a converging lens as in Fig. 2. For a metal film, imaging is not limited by the Rayleigh criterion and functions in the near field. Moreover, the metal film is truly thin—much thinner than a so-called *thin* lens. There has been a flurry of activity studying not only metals, but also metamaterials designed to give NR for imaging applications. Design and fabrication of negative-index metamaterials working at optical frequencies is difficult due to the necessity of intricate nanoscale features. Even more difficult is the fabrication of 3D negative-index metamaterials operating at optical frequencies.

Our work during this reporting period was to exploit aspects of NPCs and NPAs hitherto not discussed in the literature. We are interested in their electromagnetic properties in the context of imaging optics. NPCs and NPAs are predicted to exhibit novel vector-field, NR effects that may be more difficult to achieve in purely dielectric structures. We will study the *vector* imaging properties of NPCs and NPAs, and explore possible applications in optical vector beam filters and generators.

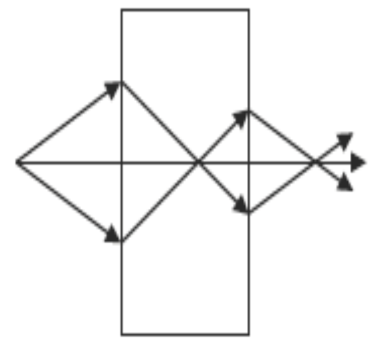

Fig. 2: The slab represents a NR material than bends light to a negative angle at the interfaces with the surrounding dielectric. A point source on the left is brought to a focus on the right. From Ref. 41.

Approach: Great impetus to the study of SPPs in NPCs and NPAs was provided by the observation that SPPs may be guided modes with transverse dimensions much less than λ/2—a feat impossible with a conventional dielectric waveguide. This in turn recommended SPPs in NPCs for nanoscale optical interconnects. As discussed above, the push toward such applications was slowed due to the radiative and nonradiative losses, and the need to keep the NPCs well apart to avoid cross-coupling. Because there are ways to solve these problems, we deem it worth pursuing novel phenomena based on the optical properties of NPCs and NPAs.

While researchers in the area were chastened by the difficulties, interest in SPPs in NPCs and NPAs continues unabated. While losses certainly inhibit using such structures to route signals, there remains great interest in their application in sensors and for diffractive elements along with a core group of people concerned with guided-wave optics. There has been discussion though little rigorous work on the application of NPCs and NPAs for NR. The NR effects of NP structures have a remarkable vector feature rarely considered that arises from the qualitative difference between the SPP modes associated with SP dipole moment parallel or transverse with respect to the SPP excitation wavevector in the structure **k**.

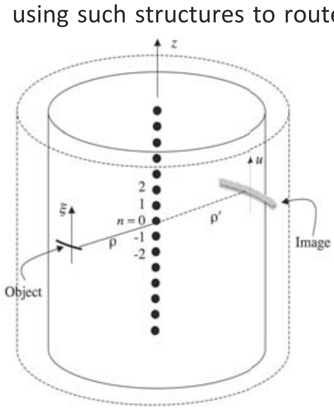

Fig. 3: Diagram of imaging geometry. Object is on cylinder of radius ρ and is imaged on a cylinder of radius ρ′. The NPC lies on the concentric axis of the cylinders. From Ref. 6.

It is known that SPPs where the dipole moment of the SPs is perpendicular to **k** decrease in frequency with increasing |**k**|. This means that the group and phase velocity associated are in opposite directions. Ruppin and Kempa pointed out that this makes simple 3D NPAs of interest for negative-index metamaterials. In work carried out under this program in previous report periods, we found that a single NPC or 2D NPA can so function.[5] A single NPC or single-layer 2D NPA would *truly* be a nanoscale focusing optical element. To understand how such a small structure functions optically, it is necessary to abandon concepts of bulk refractive indices and consider the nonlocal optical properties.

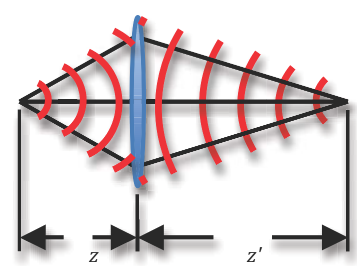

Fig. 4: A convex lens images an object a distance z in front of the lens at a point z′ behind the lens according to the thin-lens equation $z^{-1}+z'^{-1}=f^{-1}$ where *f* is the focal length.

By way of illustration, consider an infinite NPC along the *z* axis as in Fig. 3 with $d<\lambda/2$. Let the NPC be illuminated by a monochromatic arc source distance ρ from the NPC at $z=0$. We assume a vector Fourier optics viewpoint in the

Fresnel limit, in which case the point source produces a quadratic phase variation in the field along the NPC. Depending on the source, we can decompose the field into polarization components parallel or perpendicular to *z*, which are treated separately. This is similar to a diffraction problem; however, all orders of multiple scattering between NPs are treated exactly. In other words, nonlocality is an essential feature, and the effect of the NPC cannot be described in terms of a refractive index.

A key parameter in describing an imaging system is the quadratic phase *q* that appears in the amplitude transfer function of an optical system. For example, a convex lens images an object a distance z in front of the lens at a point z′ behind the lens according to the thin-lens equation $z^{-1}+z'^{-1}=f^{-1}$ where *f* is the focal length. In this case, the total quadratic phase from object to image is zero; the phase fronts are shown in Fig. 4. We turn to the situation of interest, namely the NPC. Figure 5 shows the total quadratic phase $q(\zeta)$ on propagating from object to image for the NPC; $\zeta=k/d$ is the wavevector of the SPP resonant with the light frequency. Positive ζ corresponds to polarization along the NPC axis [which gives $q(\zeta)>0$] and negative ζ correspond to perpendicular polarization [both $q(\zeta)>0$ and $q(\zeta)<0$ possible]. When $q(\zeta)=0$, the total quadratic phase involved in propagating from object to image, including interacting with the NPC vanishes, which means *the image is brought to a focus*. ***In contrast to the case of the thin metal film, imaging can be achieved both in the far and near field***.

The example above is in an unconventional cylindrical geometry because it leads to tractable results;[6] this work was carried out during the current reporting period. An array of parallel NPCs that is not too closely spaced—though what too closely means in a quantitative sense yet to be investigated—is expected to function like a cylindrical lens for the polarization perpendicular to the NPC axes.

Potentially more interesting is a 2D NPA; a manuscript treating this case is to be submitted shortly. As mentioned above, the group and phase velocities associated with SPP modes polarized transverse to the excitation wavevector **k** in the NPA are in opposite directions providing favourable conditions for focusing for these spatial Fourier components of the field; preliminary theoretical results suggest this is indeed the case. Even without considering the image itself, the NPA thus can serve as an optical vector beam (OVB) filter or generator. OVBs[7] (see Fig. 6) broadly speaking are freespace optical modes that are polarized in the radial direction with respect to the beam axis (maps roughly to the polarization parallel to **k**) and azimuthal direction with respect to the beam axis (maps roughly to the polarization perpendicular to **k**). The beams are modulated by a sinusoid in the azimuthal direction around the beam axis. Due to the resulting phase singularity on the optical axis, these beams must have a null at beam centre leading to their sometimes being called *donut* or *cylindrical* beams. OVBs have attracted interest for optical trapping, microscopy, single-molecule dipole-moment mapping, and optical particle acceleration.[7]

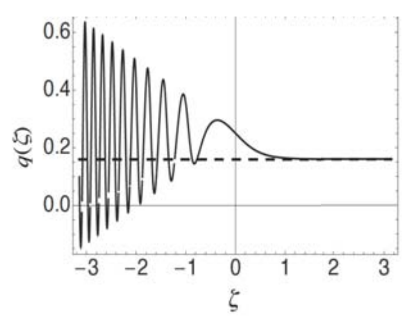

Fig. 5: $q(\zeta)$ in z direction as a function of excitation wavevector ζ resonant with object. Horizontal dashed line shows quadratic phase associated with propagation from object to NPC, and from NPC to image; thus, it does not account for effect of NPC. When $q(\zeta)=0$, an imaging geometry results. This only applies for polarization perpendicular to NPC axis. From Ref. 6.

The 2D geometry just as discussed would be useful to filter out the radial or axial components of the beam, and thus serve as an unprecedentedly simple device to do so. The above discussion has neglected the underlying symmetry of the NPA—such as a square or rectangular lattice. This underlying lattice results in *warping* of the SPP dispersion (angular dependence in **k**-space) that arises due to longitudinal-transverse mixing between the SPPs polarized parallel and perpendicular to **k**.[5] This azimuthal modulation of the imaging property of the NPA is expected to manifest itself as a modulation of the field amplitude, thus preferentially selecting the azimuthal order (number of nulls as a function of angle around the optical axis) of the beam.

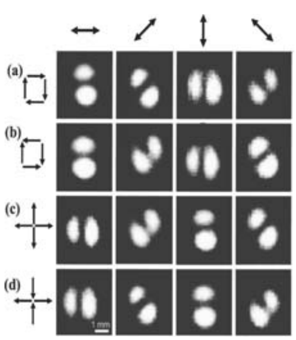

Fig. 6: OVB intensity distributions viewed on beam axis. Arrows indicate electric-field direction across beam. (a) and (b) are axial beams; (c) and (d) are radial beams. From Ref. 7.

The production of OVBs—even the filtering proposed—today requires a significant optical system[7]. If the NPA functions as we have described, a single periodic layer of NPs can replace much more complicated optical systems. The azimuthal/radial mode filter would vastly simplify the production of optical vector modes in a compact system.

Currently, we have preliminary results for the quadratic phase for the NPA, and a manuscript is in preparation. We find that while the *T*-mode cannot provide focusing to satisfy the lens equation, T-polarized components of the field undergo less net defocusing than L-polarized components. This means that with an additional focusing lens and spatial filtering, it should be possible to isolate the *T*- or *L*-polarized components as desired. Specifically, we have obtained the point spread function (PSF) for the NPA in system relating an object field a distance *z* in front of the NPA and an image field a distance *z′* behind the NPA. From the PSF, we have computed the image field (basically the beam emerging from the NPA) for a small linearly polarized source, and have shown that this produced spatially separable radially and azimuthally polarized beams with two nodes as one goes around the optical axis (i.e., in the azimuthal direction), demonstrating in principal the generation of nontrivial OVBs.

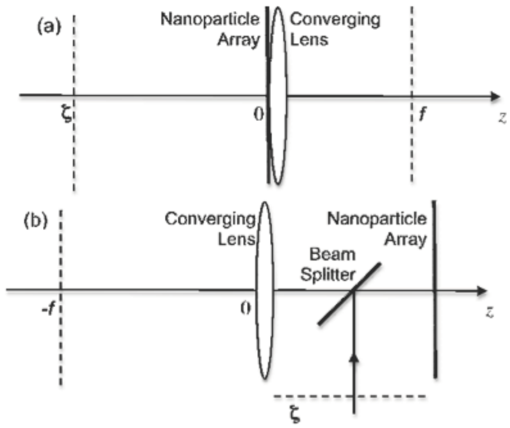

Fig. 7: (a) Schematic diagram of geometry. Linearly polarized Gauss or Bessel beam is normally incident from -z direction; coordinates in plane z=ζ in the incident beam are denoted ρ. For z>0, forward-propagating pure radial and azimuthal OVBs occur at focal backplane z=f of converging lens; coordinates in plane z=f are denoted ρ′. Alternative setup (b) has beam incident from the z=ζ plane, and passes through beam splitter before impinging on NPA. Reflected beam from NPA passes through converging lens and produces OVB at focal backplane of converging lens at z=-f. Note that the elements are viewed edgewise. From Ref. [12].

In addition, one graduate student is working on adapting FDTD code in our group to treat plasmonic structures (such as NPAs), nanophotonic structures, and photonic crystals,[8-10] while a second student has been pursuing nonlinear dynamics in laser diodes as we plan to study the modification to the dynamics due to proximate nanoplasmonic structures in a chaos-communications context. The PI has also been involved in the evaluation of a hitherto unevaluated Kapteyn series of the second kind that appears in some modulated optical systems.[11]

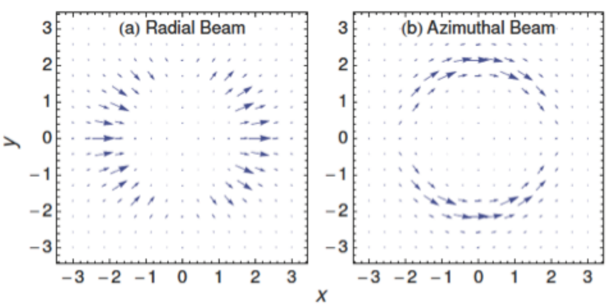

Fig. 8: Electric field of beam in lens focal backplane (see Fig. 7) in arbitrary units. (a) and (b) show radially or azimuthally polarized beam, depending whether frequency coincides with longitudinal or transverse SPP dispersion curve, respectively. Form Ref. [12].

Two manuscripts have been submitted subsequent to the closing of this program, though the theoretical framework was laid down under funding from 0523923. This work focuses on two-dimensional NPAs and other two-dimensional structures that exhibit strong dependence of their optical properties on whether incident light is *s*- or *p*-polarized with respect to the plane defining the structure.[12,13] We imagine an optical system such as in Fig. 7. Consider an incident optical beam (we have treated Gaussian and Bessel beams) from the z=ζ plane. This beam can be decomposed into its spatial Fourier components, which can be further resolved into their *s*- and *p*-polarized components with respect to the NPA plane. Because the *s*-polarized light coupled to transverse SPPs while *p*-polarized light couples to longitudinal SPPs, each of which has a distinct dispersion surface, the *s*- and *p*-polarized components of the incident beam undergo entirely different filtering by the NPA. If the incident frequency is chosen judiciously, the transmitted beam can be predominantly *s*- or *p*-polarized, that is azimuthally or radially polarized, respectively, in k-space. Because of the Fourier-transforming property of a converging lens at its focal backplane, the field there in real space is then entirely azimuthally or radially polarized, respectively. Examples of such OVBs in the focal backplane are shown in Fig. 8 (see Ref. [12] for explanation of scale).

The subject of Ref. [13] is similar, but in this case, in the system shown schematically in Fig. 7(b), the NPA is replaced by a dielectric interface between, say air, and a material with a higher dielectric constant to the right of the interface. The incident beam is here chosen to be a Bessel beam whose spatial frequencies correspond to the Brewster angle θ_B. The point is that all spatial Fourier frequencies of a Bessel beam have the same magnitude, say k_{2D}. Thus, we need to choose k_{2D}=k tan θ_B. Since the reflected beam is purely *s*-polarized, the field in the focal backplane of the lens is purely azimuthally polarized. We are currently generalizing this to explore the OVB in systems dispensing with the converging lens to understand the spatial distribution of the polarization in more generality.

Intellectual Merit: The idea of vector lensing is entirely new to our knowledge. The understanding of the basic optical properties of NPCs and NPAs for incident fields external to the structures (i.e., as opposed to guided waves) is unaddressed as a serious nonlocal vector electromagnetics problem. The ability of NPCs and NPAs to provide vector lensing may enable entirely new classes of flat and nanoscale optical elements and filters.

Broader Impact: Optical elements based on vector-lensing principals may eventually enable commercial implementation of certain types of superresolution imaging for microscopy, optical manipulation of single molecules, and three-dimensional vector microscopy. The program during this reporting period has supported graduate student research and training.

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